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A WORKING MODEL OF THE ATMOSPHERE OF VENUS

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16. Abstract

Research carried out on a working model of the atmosphere of Venus was based on observations and measurement done by Soviet and American spacecraft. The model gives the distribution of temperature, pressure and density in the atmosphere of Venus, concluded from information available up to November 1973. Data were analyzed in pressure ranges of 0.1-1 atmosphere. Evaluations are given of solar and scattered illuminance in the upper part of the cloud layer, and also of thermal flows and wind speeds.

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A WORKING MODEL OF THE ATMOSPHERE OF VENUS

V.I. Moroz

Introduction /3*

Five Soviet spacecraft carried out direct measurement of temperature, pressure and other basic parameters of the atmosphere of Venus in an altitude range of 0 to 55-58 km. In the interval from 40 to 80 km, the atmosphere was studied by radioscopy when the American spacecraft Mariner-5 passed close to the planet.[1]

The present model summarizes these and other results. It shows the distribution of temperature, pressure and density according to altitude in the atmosphere of Venus, taking into account all information which the compiler had at his disposal for November 1973. Special attention is paid to analyzing information in the pressure area 0.1-1 atmosphere. Evaluations were carried out of illuminance (solar and diffused) in the upper cloud layer, and also of heat fluxes and wind speed, which can be recommended for technical calculations.

1. Chemical Composition of the Atmosphere /4

The basic component of the atmosphere of Venus is CO_2. According to measurement results carried out by V4, 5 and 6 spacecraft using chemical gas analyzers, its volumetric percentage content is 97^{+3}_{-4} [1]. The total upper limit of nitrogen and inert gas content does not exceed 2%, oxygen -- 0.1%. At a level of 0.6-2 atm., the sensors of V4, 5 and 6 observed approximately 1% H_2O; however, there is some contradiction with

[1]For brevity, spacecraft Venus-4, 5, 6, 7, 8 and Mariner-5 will be designated V4, 5, 6, 7, 8 and M5.

*Numbers in the margin indicate pagination in the foreign text.

Earth spectroscopy, which gives two orders less for some greater altitudes. Chemical sensors on V8 [2] found traces of NH_3 (0.01-0.1%), which also slightly exceeds the spectroscopic upper limit ($\sim 10^{-6}$%). Spectroscopic observations, on the other hand, detected small amounts of CO, HCl and HF [3, 4]. A summary of the basic information on the chemical composition is shown in Table 1. It does not include spectroscopic upper limits which are known for many compounds (see, for example, [5]).

For calculating the model of the atmosphere, the content of CO_2 will be taken as 100% (and correspondingly the molecular weight 44.0) in a range of altitudes from 0 to 150 km. The difference in models with a 100% and 95% CO_2 (remainder N_2) is less than errors in the initial values of temperature and pressure, especially in the range of altitudes where they must be extrapolated by theoretical models.

2. Temperatures, Pressures and Densities

In Venus descent vehicles (DV) the temperature was measured with resistance thermometers, and the pressure with aneroid sensors [6, 7]. Apart from which, an ionization densitometer was used for measuring density on the V4 [6], and a tuning-fork densitometer on V5 [8]. The experiment produced T, P and /5
ρ directly in the time function as the DV descended by parachute. A radio-location altimeter was used on V5, V6 and V8 for absolute conjunction in altitude. Relative altitudes were determined more reliably by integrating a hydrostatic balance equation from the equation of motion of the DV. Measurement on the DV embraced a range from 0 to 58 km; however, in its upper section (above 40-50 km), the accuracy of the direct determinations of pressure and temperature was smaller than that of the radio refraction experiment on M5 [9]. Therefore, beginning at 40 to 75 km pressure and temperature profiles will be used which were obtained by the American spacecraft. In work [9] three pairs of such

profiles were published (the night side according to the Doppler effect and attenuation, the day side according to the Doppler effect), and are very close to each other. They were averaged for compiling the present model.

Figure 1 shows the P-T diagram for the atmosphere of Venus on which results of Soviet direct and American radio-refraction measurements have been plotted. This presentation of information is more convenient, since it does not depend on their altitude conjunction. Probable errors of direct measurement are estimated approximately according to data given in works [10, 11]. Here there is also an adiabat for 100% CO_2 (with allowance for the dependency of c_p on P and T according to Tables [12]). The following two conclusions can be made from examination of this diagram:

1) both basic sets of measurements of P, T (direct and refraction) agree well,
2) lower than level P = 2 atm., T = 370°K measurement in limits of errors are satisfactorily shown by an adiabat for pure CO_2.

In altitude ranges where the dependents P, T were experimentally obtained, the conjunction of values for these parameters to altitudes was determined when compiling a working model by using a barometric formula. In the case of linear dependency T on height Z, the latter has the form: /6

$$P_{i+1} = P_i \left(\frac{T_{i+1}}{T_i}\right)^{-\frac{g}{R\, dT/dz}} \quad (1)$$

or in the adiabatic range:

$$P_{i+1} = P_i \left(\frac{T_{i+1}}{T_i}\right)^{\frac{c_p}{R}} \quad (2)$$

$$\frac{dT}{dz} = -\frac{g}{c_p}, \quad (3)$$

where P_i and T_i are pressure and temperature on a certain level i; P_{i+1}, T_{i+1}, the pressure and temperature on the following level; g, the acceleration of gravity (880 $cm \cdot sec^{-2}$ on the surface); $R = 0.189\ J \cdot g^{-1} \cdot deg^{-1}$ is the gas constant for CO_2; c_p is the heat capacity during constant pressure.

A level with temperature T = 750°K was taken as the initial one. A temperature of 741 ± 7°K and a pressure of 93 ± 1.5 atm. was measured where the V8 landed [11]. Adiabatic extrapolation to a level of 750°K gives a pressure of 100 atm. with an indeterminacy of ±7%, allowing for error in initial values of temperature and pressure. Joining the adiabat with the initial level,

$$T_0 = 750°K;\ P_0 = 100 \pm 7 \text{ atm.}$$

and Mariner data on the distance to the center of the planet, allows one to determine this distance for our initial level. It equals R_0 = 6051 km. This selected initial level corresponds to conditions in the landing area of V7 and is 1 km lower than the level of the landing area of V8. The actual mean level of the surface, apparently, does not differ from R_0 by more than 1-2 km. R_0 in limits of errors coincides with the radio-location radius of Venus (6050 ± 5 km, see [13]).

The dependence T(Z), P(Z) was calculated by an adiabat in /7
the altitude interval $Z = R - R_0$ from 0 to 40 km. Higher, up to 75 km, the direct "refraction profile" was used, obtained by averaging Mariner data shown in work [9]. Above 75 km, three hypothetical variants of temperature profile were used which were compiled with respect to existing theoretical models [14, 15]. These profiles are shown in Fig. 2. A concentration of neutral molecules in the ionosphere can be used for a rough check of the accuracy of the profile at great altitudes. It must be approximately 10^{10} cm^{-3} at altitudes of 150-160 km. This

criterion does not satisfy a model with a thermal mesopause (of the type shown in work [8]), although it agrees better with results of observations of the occultation of Regulus by Venus [16, 17]. However, the latter are too inaccurate (the altitude scale is determined with an error of approximately 50%).

Three variants of the working model were calculated -- the basic, the maximum and the minimum (Tables 2-4 and Figs. 2, 3). On the section from 0 to 70 km, the maximum and minimum models scarcely differ from the basic -- the temperature profile is general, pressures and densities are accepted as 10% greater in the maximum model, and in the minimum model, 10% smaller than in the basic. Above 70 km, a hypothetical profile with higher temperatures is used in the maximum model; in the minimum model, a lower one than the basic.

The basic model is close to that published earlier in work [5]. Marked differences from the so-called "second" Institute of the Problems of Mechanics model [18] are found in two areas: 45-60 km (the temperatures in our model were more than 20-30°), and above 70 km, where another temperature profile is also used. In maximum and minimum models, the profile of T at great altitudes varies more widely than was shown in work [18].

Daily temperature and pressure variations can be reckoned as negligibly small up to altitudes of not lower than 80 km.

3. An Optical Model of a Cloud Layer. The Illuminance in the Upper Part of the Cloud Layer /8

Existing data on the basic optical characteristics of the cloud layer can be divided into three groups:

a) results of ground photometric and polarimetric observations, giving information on the scattering indicatrix and reflective power of particles of the cloud layer in its upper part,

b) results of spectroscopic observations, the analysis of which by using a model of the atmosphere allows one to evaluate the mean scattering coefficient in the upper part of the cloud layer,

c) measurement of the illuminance in the lower part of the cloud layer and in the sub-cloud atmosphere on the Venus-8 DV [19].

A short summary of the results of ground observations can be found in work [5]. In the spectrum range 0.6-1.1 μm the spherical albedo is approximately 0.90. The scattering indicatrix $x(\gamma)$ is elongated forward, the value of parameter

$$x_1 = \frac{3}{2}\int_0^{\pi} x(\gamma)\cos\gamma \sin\gamma \, d\gamma$$

characterizing the amount of elongation is 2.0-2.1.

Interpretation of spectroscopic observations gives a volumetric scattering coefficient in the upper part of the cloud layer:

$$\sigma = 2 \cdot 10^{-5} \text{ cm}^{-1}$$

with an indeterminacy of 2-3 times. For further calculations of the illuminance inside the cloud layer, it is suitable to use parameter

$$\varepsilon = \sqrt{\frac{1-a}{3-x_1}} = \frac{1-A}{4} = 0.025 \qquad (4)$$

where a is the single scattering albedo, A is the spherical albedo of the planet. Another parameter we need is the product:

$$\varepsilon\sigma = 5 \cdot 10^{-7} \text{ cm}^{-1} \qquad (5)$$

The altitude of the upper boundary of the cloud layer Z_c is evaluated by several methods, giving close results:

a) measurement of the optical diameter of the planet near the superior conjunction gives altitudes of Z_c = 60-70 km with a rather large indeterminacy, not less than 10 km [20, 21], /9

b) absorption bands of CO_2 are formed during effective pressures from 0.02 to 0.3 atm. [22-24], where a 0.1 atm. which corresponds to $Z_c \approx 65$ km can be taken as the average value,

c) rotary temperatures of weak bands of CO_2 on an average are approximately 250°K [22], which corresponds to $Z_c \simeq 65$ km.

It is possible that the upper boundary of the cloud layer is diffuse and has a complex vertical and horizontal structure. In high latitudes (ψ = 50-70°), its altitude, apparently, is 5-7 km less than in the equatorial [24]. There are also indications of longitudinal variations of altitude with an amplitude of several km. Above the upper boundary of the main cloud layer, there are fine "ultraviolet" clouds, extending to altitudes of 95-100 km [25].

Direct measurement of illuminance on the V8 spacecraft made it possible to fix the position of the lower boundary of the cloud layer -- its altitude is approximately 35 km [19]. The ratio of illuminance on the lower boundary of the cloud layer to that on the upper boundary is:

$$T = \frac{E}{E_0 \sin h} \simeq 0.05^{+0.05}_{-0.02},$$

Here E_0 is illuminance for normal incidence outside of the atmosphere, h is the height of the Sun above the horizon (5.5 ± 2.5°). The maximum of the spectral characteristic of a photometer is approximately 6600 Å, its width with respect to level 0.5 is approximately 2000 Å.

For an optically uniform dispersive layer with small true absorption

$$T = u(h) e^{-k\tau_0}, \qquad (6)$$

where $\tau_0 = 6\ell$ is the optical thickness of the layer (ℓ is the geometric thickness), u(h) is the height of the Sun above the horizon:

$$\text{[illegible]} \sin h \approx 0.6, \qquad (7)$$

from which

$$k\tau_0 \simeq 2.5^{+0.5}_{-0.7}.$$

by accepting ℓ = 30 km, we find

$$k\sigma = 6 \pm 2 \cdot 10^{-7}\ \text{cm}^{-1} \qquad (8)$$

which agrees with an evaluation (5) obtained by ground observations. For us, this conformity is a basis for believing that the cloud layer of Venus in the first approximation is uniform over its whole thickness.

Table 5 shows the basic parameters of three optical models of the cloud layer of Venus -- medium, maximum and minimum (according to illuminance) and the values of coefficients shown are:

$$T_{\downarrow} = \frac{E_{\downarrow}}{E_0 \sin h} \qquad (9)$$

and

$$T_{\uparrow} = \frac{E_{\uparrow}}{E_0 \sin h}, \qquad (10)$$

where $E_{\downarrow}$ is the illuminance of the horizontal area from above, equal to the sum of the attenuated solar radiation and the radiation scattered diffusely by a cloud, $E_{\uparrow}$ is illuminance of the horizontal area from below by diffusely scattered radiation.

Models showing the three basic parameters are:

a) the altitude of the upper boundary of the cloud layer Z_c,
b) the parameter $\kappa\sigma$,
c) single scattering albedo a.

For each model there is also a volumetric scattering coefficient σ and in tables there is an optical depth $\tau = \sigma(z_c - z)$
Calculation was done to level Z = 50 km. Calculation of illuminance was done according to V.V. Sobolev approximation formulas [26]. Values of T shown in Table 5 can be used directly in the range of angles

$$30° < h < 90°$$

When h = 30° one must multiply them by the correction factor u, found by formula (7). The calculated values of T are suitable for evaluating the illuminance in the wavelength interval from /11
6000 to 11,000 Å. Monochromatic extra-atmospheric illuminances of an area normal to solar rays on an average distance of Venus from the Sun are shown in Table 6.

Models shown in Table 5 do not allow for the attenuation of light which can take place in a rarefied haze above clouds. It can reduce the values of T, shown in the table, by 10-20%.

There are two factors which are derived from the models shown:

a) the illuminances from above and below differ little even near to the upper boundary of clouds,

b) there is no abrupt change whatsoever of illuminancy at the intersection of the upper boundary; as the cloud layer becomes deeper, the illuminance gradually decreases with altitude.

The preliminary nature of the proposed optical model and the need to refine it by new experiments must be stressed emphatically.

Table 7 gives evaluations of the brightness of Venus which are useful for calculating the sensitivity of photometric and spectral instruments. They are based mainly on results of work [27], however, other information was used for evaluating the expected deviations from the Lambert law. In Table 7, the brightness values are approximate and deviations of 20-30% are possible.

4. Thermal Radiation Flows in the Atmosphere

A thermal radiation flow, going into outer space, is determined by the amount of solar radiation absorbed by the planet

$$\Phi = \frac{1}{4}(1 - A_{int})\Phi_{\odot}, \tag{11}$$

where A_{int} is the integral spherical albedo, $\Phi_{\odot}$ is the solar /12
constant, derived from averaging the distance of Venus from the Sun. According to [27]

$$A_{int} = 0.77 \pm 0.07 \tag{12}$$

from where, by accepting $\Phi_{\odot} = 2680\ W \cdot m^{-2}$, we find:

$$\Phi = 154\ W \cdot m^{-2} \tag{13}$$

for an average value of $A_{int} = 0.77$. If $A_{int_2} = 0.84$, $\Phi = 107\ W \cdot m^{-2}$; if one accepts $A_{int} = 0.70$, then $\Phi = 201\ W \cdot m^{-2}$. In this way, the indeterminacy in the value of the departing flow is large -- approximately twice as large.

The spectrum of departing radiation in the range from 3.5 to 20 μm, according to ground observations [28] does not indicate a noticeable striated structure, the brightness temperature hardly changes from the wavelength. It is approximately equal to the temperature on the upper boundary of the cloud layer, the position of which is determined independently from other observations (see Section 3). Both these factors mean that during the transfer of thermal radiation particles of the cloud layer itself play a decisive role, and the absorption coefficient depends very little on the wavelength. Therefore, one must use an approximation of the "gray" atmosphere for calculating heat flows (that is, atmosphere with an absorption coefficient, independent of the wavelength). In this case, the radiation flux into the upper hemisphere is

$$F_{\uparrow} = \sigma T^4 + \frac{1}{2}\Phi, \tag{14}$$

the radiation flux into the lower hemisphere

$$F_{\downarrow} = \sigma T^4 - \frac{1}{2}\Phi, \tag{15}$$

where T is the temperature at a certain altitude.

In atmosphere above clouds, one can accept

$$F_{\uparrow} = \Phi_{15}(T,P) + \Phi, \tag{16}$$

$$F_{\downarrow} = \Phi_{15}(T,P), \tag{17}$$

where $\Phi_{15}(T,P)$ is the flow in the 15-μm CO_2 band. /13

At an altitude of approximately 70 km, both pairs of formulas give close results. Beginning at 65 km and below, we use formulas (14) and (15) for calculating flows, and formulas (16) and (17) for altitudes above 65 km. Results are given in Table 7 for three values of Φ -- three models were obtained, respectively: the basic, corresponding to the mean value of Φ, the maximum and minimum. They differ mainly in the upper part of the investigated area; as the altitude decreases the models converge, since flows of F are close to equilibrium black-body values. During calculation it was presumed that $H = F_{\uparrow} - F_{\downarrow}$ did not depend on altitude; in an actual atmosphere, it can be expected that the value of H is reduced in the upper part of the cloud layer with a reduction of altitude, and values of $F_{\uparrow}$ and $F_{\downarrow}$ converge to a mean $\bar{F} = \frac{1}{2}(F_{\downarrow} + F_{\uparrow}) = \sigma T^4$. The difference between night and day flows is negligibly small.

5. Wind Speeds

There are three sources of information on wind speed in the atmosphere of Venus:

a) movements of ultraviolet clouds [29],
b) the movement of visible clouds, determined according to the Doppler shift [30], and by the periodic changes of CO_2 bands,
c) the horizontal shift of Soviet DV, determined by the Doppler shift of the carrier frequency of radio signals [11, 31].

The first two sources relate to the 60-90 km range of altitudes and, on an average, give speeds of approximately 100 m/sec. The third source made it possible to show the profile of horizontal wind speed in altitude ranges from 0 to 50 km. This /14 profile, according to information from V8, consists of three sections: the lower (0-10 km), where the speed does not exceed 3 m/sec, the medium (20-40 km), where the wind speed is approximately 35 m/sec, and the upper (40-50 km), where the wind speed increases to 60 m/sec.

A concept of the order of magnitude of vertical speeds can be obtained from comparing the descent speeds of DV, calculated by a barometric formula and the aerodynamic braking equation. These coincide with an accuracy of up to several meters/seconds. 2 m/sec can be accepted as the upper limit. This evaluation relates directly to altitudes of 0-50 km. Extrapolation of it to greater altitudes is permissible since there is a complete lack of any other information.

TABLE 1. THE CHEMICAL COMPOSITION OF THE ATMOSPHERE OF VENUS (MOLECULES, RELIABLY DETECTED). /17

Molecule	Relative Concentration	Literature
CO_2	97^{+3}_{-4}	[1]
H_2O	0,01 – 1,0	[1,5]
CO	$5 \cdot 10^{-5}$	[3]
HCl	$6 \cdot 10^{-7}$	[3]
HF	10^{-8}	[3]

TABLE 2. THE WORKING MODEL OF THE ATMOSPHERE OF VENUS (BASIC VARIANT). /18

Distance from Center of Planet R, km	Arbitrary Height Z, km	Temperature T, °K	Pressure P, атм	Numerical Concentration n, $см^{-3}$	Density ρ, $гсм^{-3}$	Notes
6051	0	750	100	$9.65\cdot10^{20}$	$7.10\cdot10^{-2}$	Surface level, V7
6052	1	747	93.0	9.08	6.67	Surface level, V8
6056	5	712	73.0	7.43	5.46	
6061	10	674	54.6	5.87	4.32	
6066	15	635	38.2	4.26	3.13	
6071	20	595	26.1	3.18	2.34	End of work V5, V6
6076	25	555	17.6	2.30	1.69	
6081	30	514	11.4	1.61	1.18	
6086	35	472	7.2	1.11	$8.16\cdot10^{-3}$	
6091	40	428	4.0	$6.78\cdot10^{19}$	4.98	Lower boundary of
6096	45	384	2.2	4.16	3.06	the "M5 area"
6101	50	350	1.2	2.49	1.83	
6106	55	300	$5.5\cdot10^{-1}$	1.33	$9.78\cdot10^{-4}$	Beginning of work
6111	60	260	2.3	$6.41\cdot10^{18}$	4.69	of V4, V5, V6,
6116	65	240	1.0	3.02	2.22	V7, V8
6121	70	222	$4.0\cdot10^{-2}$	1.31	$9.59\cdot10^{-5}$	Upper boundary of
6126	75	213	1.41	$4.79\cdot10^{17}$	3.52	the "M5 area"
6131	80	205	$4.65\cdot10^{-3}$	1.65	1.21	
6141	90	187	$4.54\cdot10^{-4}$	$1.76\cdot10^{16}$	$1.29\cdot10^{-6}$	
6151	100	170	$3.61\cdot10^{-5}$	$1.54\cdot10^{15}$	$1.13\cdot10^{-7}$	
6161	110	177	$2.63\cdot10^{-6}$	$1.08\cdot10^{14}$	$7.93\cdot10^{-9}$	Mesopause
6171	120	183	$2.20\cdot10^{-7}$	$8.70\cdot10^{12}$	$6.39\cdot10^{-10}$	
6181	130	190	$1.98\cdot10^{-8}$	$7.55\cdot10^{11}$	$5.55\cdot10^{-11}$	Amount of eclipse
6191	140	255	$2.65\cdot10^{-9}$	$7.53\cdot10^{10}$	$5.53\cdot10^{-12}$	of Regulus
6201	150	320	$5.64\cdot10^{-10}$	$1.28\cdot10^{10}$	$9.39\cdot10^{-13}$	

TABLE 3. A WORKING MODEL OF THE ATMOSPHERE OF VENUS (MAXIMUM VARIANT).

Distance from Center of Planet R, km	Arbitrary Height, Z, km	Temperature $T, {}^{0}K$	Pressure P, атм	Numerical Concentration n, см$^{-3}$	Density ρ, гсм$^{-3}$	Notes
6051	0	750	110	$1.05 \cdot 10^{21}$	$7.81 \cdot 10^{-2}$	Surface level, V7
6052	1	741	102.3	$9.99 \cdot 10^{20}$	7.33	Surface level, V8
6056	5	712	80.3	8.17	6.00	
6061	10	674	60.0	6.45	4.75	
6066	15	635	42.0	4.68	3.44	
6071	20	595	26.7	3.50	2.58	End of work,
6076	25	555	19.3	2.53	1.86	V5, V6
6081	30	514	12.5	1.77	1.30	
6086	35	472	7.9	1.22	$8.97 \cdot 10^{-3}$	
6091	40	428	4.4	$7.45 \cdot 10^{19}$	5.48	Lower boundary of
6096	45	384	2.4	4.58	3.36	the "M5 area"
6101	50	350	1.3	2.74	2.01	
6106	55	300	$6.0 \cdot 10^{-1}$	1.46	1.08	Beginning of work of
6111	60	260	2.5	$7.05 \cdot 10^{18}$	$5.16 \cdot 10^{-4}$	V4, V5, V6,
6116	65	240	1.1	3.32	2.44	V7, V8
6121	70	222	$4.4 \cdot 10^{-2}$	1.44	1.05	Upper boundary of
6126	75	220	1.55	$5.11 \cdot 10^{17}$	$3.76 \cdot 10^{-5}$	the "M5 area"
6131	80	218	$5.43 \cdot 10^{-3}$	1.81	1.33	
6141	90	213	$6.76 \cdot 10^{-4}$	$2.30 \cdot 10^{16}$	$1.69 \cdot 10^{-6}$	
6151	100	209	$7.87 \cdot 10^{-5}$	$2.73 \cdot 10^{15}$	$2.01 \cdot 10^{-7}$	Mesopause
6161	110	204	$9.00 \cdot 10^{-6}$	$3.19 \cdot 10^{14}$	$2.34 \cdot 10^{-8}$	Amount of
6171	120	200	$9.66 \cdot 10^{-7}$	$3.50 \cdot 10^{13}$	$2.57 \cdot 10^{-9}$	eclipse of
6181	130	267	1.40	$3.80 \cdot 10^{12}$	$2.79 \cdot 10^{-10}$	Regulus
6191	140	333	$3.16 \cdot 10^{-8}$	$6.86 \cdot 10^{11}$	$5.04 \cdot 10^{-11}$	
6201	150	400	$9.44 \cdot 10^{-9}$	$1.71 \cdot 10^{11}$	$1.26 \cdot 10^{-11}$	

TABLE 4. A WORKING MODEL OF THE ATMOSPHERE OF VENUS (MINIMUM VARIANT). /20

Distance from Center of Planet R, km	Arbitrary Height Z, km	Temperature $T, {}^{\circ}K$	Pressure P, атм	Numerical Concentration n, $см^{-3}$	Density ρ, $см^{-3}$	Notes
6051	0	750	90	$8.69\cdot10^{20}$	$6.39\cdot10^{-2}$	Surface level, V7
6052	1	741	83.6	8.17	6.00	Surface level, V8
6056	5	712	65.7	6.68	4.92	
6061	10	674	49.1	5.28	3.89	
6066	15	635	34.4	3.83	2.82	End of work, V5, V6
6071	20	595	23.4	2.86	2.11	
6076	25	555	15.8	2.07	1.52	
6081	30	514	10.3	1.45	1.06	
6086	35	472	6.5	1.00	$7.35\cdot10^{-3}$	
6091	40	428	3.60	$6.10\cdot10^{19}$	4.48	Lower boundary of the "M5 area"
6096	45	384	1.98	3.74	2.76	
6101	50	350	1.08	2.24	1.65	
6106	55	300	$4.95\cdot10^{-1}$	1.20	$8.80\cdot10^{-4}$	Beginning of work of V4, V5, V6, V7, V8
6111	60	260	2.07	$5.77\cdot10^{18}$	4.22	
6116	65	240	$9.00\cdot10^{-2}$	2.72	2.00	
6121	70	222	3.60	1.18	$8.63\cdot10^{-5}$	Upper boundary of the "M5 area"
6126	75	210	1.26	$4.35\cdot10^{17}$	3.20	
6131	80	198	$4.13\cdot10^{-3}$	1.51	1.11	
6141	90	174	$3.60\cdot10^{-4}$	$1.50\cdot10^{16}$	$1.10\cdot10^{-6}$	
6151	100	150	$2.20\cdot10^{-5}$	$1.06\cdot10^{15}$	$7.81\cdot10^{-8}$	Mesopause
6161	110	157	$1.15\cdot10^{-6}$	$5.32\cdot10^{13}$	$3.91\cdot10^{-9}$	Amount of eclipse of Regulus
6171	120	163	$7.15\cdot10^{-8}$	$3.17\cdot10^{12}$	$2.33\cdot10^{-10}$	
6181	130	170	$4.88\cdot10^{-9}$	$2.08\cdot10^{11}$	$1.53\cdot10^{-11}$	
6191	140	215	$4.78\cdot10^{-10}$	$1.61\cdot10^{10}$	$1.18\cdot10^{-12}$	
6201	150	260	$7.35\cdot10^{-11}$	$2.05\cdot10^{9}$	$1.50\cdot10^{-13}$	

TABLE 5. OPTICAL MODELS OF THE CLOUD LAYER. /21

Model	Basic			Maximum (acc. to illuminance)			Minimum (acc. to illuminance)		
Altitude of upper boundary z_0, км	67.5			65			70		
σ, $см^{-1}$	$2\cdot10^{-5}$			$1\cdot10^{-5}$			$1\cdot10^{-5}$		
κ	0.022			0.01			0.032		
$\kappa\sigma$, $см^{-1}$	$4.4\cdot10^{-7}$			$1.0\cdot10^{-7}$			$1.3\cdot10^{-6}$		
$1-a$	$5\cdot10^{-4}$			$1\cdot10^{-4}$			$1\cdot10^{-3}$		
Altitude z, км	τ	$T_{\downarrow}$	$T_{\uparrow}$	τ	$T_{\downarrow}$	$T_{\uparrow}$	τ	$T_{\downarrow}$	$T_{\uparrow}$
70	0	1.00	0.91	0	1.00	0.96	0	1.00	0.87
67.5	0	1.00	0.91	0	1.00	0.96	10	0.73	0.64
65	5	0.90	0.82	0	1.00	0.96	20	0.53	0.46
62.5	10	0.80	0.73	2.5	0.98	0.94	30	0.40	0.30
60	15	0.72	0.66	5	0.95	0.91	40	0.28	0.24
55	22.5	0.63	0.58	10	0.90	0.86	60	0.16	0.13
50	30	0.54	0.48	15	0.86	0.82	80	0.08	0.07

TABLE 6. ILLUMINANCES ON THE UPPER BOUNDARY OF THE CLOUD LEVEL IN THE RANGE 6000-11,000 Å ($E_0 \sin h$). /22

Height of Sun above Horizon	Monochromatic Illuminance $W \cdot cm^{-2} \mu m^{-1}$					
	6000Å	7000Å	8000Å	9000Å	10000Å	11000Å
90°	0.347	0.276	0.216	0.171	0.139	0.116
60	0.300	0.239	0.189	0.148	0.120	0.100
30	0.173	0.138	0.108	0.085	0.070	0.058
10	0.062	0.047	0.038	0.030	0.024	0.020

TABLE 7. EXPECTED BRIGHTNESSES OF VENUS IN THE RANGE 3000-20,000 Å.

Wavelength Å	Brightness, $W \cdot cm^{-2} ster^{-1} \mu m^{-1}$ Height of Sun above Horizon (Phase Angle 70°) *		
	90°	40°	20°
3 000	0.023	0.013	0.006
3 500	0.052	0.030	0.013
4 000	0.076	0.044	0.019
5 000	0.108	0.063	0.027
6 000	0.108	0.063	0.027
7 000	0.096	0.056	0.024
8 000	0.074	0.043	0.019
16 000	0.014	0.008	0.004
20 000	0.006	0.004	0.001

*Brightnesses are given on the intensity equator.

TABLE 8. EXPECTED THERMAL RADIATION FLOWS IN THE ATMOSPHERE OF VENUS (ALTITUDE RANGE 50-80 km).

Altitude Z, km	T, °K	P, atm.	Basic Model $A_c = 0.77$ T=228°K, σT^4=154 $W \cdot m^{-2}$		Maximum Model $A_c = 0.70$ T=245°K, σT^4=2.01 $W \cdot m^{-2}$		Minimum Model $A_c = 0.84$ T=209°K, σT^4=1.07 $W \cdot m^{-2}$	
			Flow into Upper Hemisphere $F_\uparrow$, $W \cdot m^{-2}$	Flow into Lower Hemisphere, $F_\downarrow$, $W \cdot m^{-2}$	Flow into Upper Hemisphere $F_\uparrow$, $W \cdot m^{-2}$	Flow into Lower Hemisphere, $F_\downarrow$, $W \cdot m^{-2}$	Flow into Upper Hemisphere, $F_\uparrow$, $W \cdot m^{-2}$	Flow into Lower Hemisphere, $F_\downarrow$, $W \cdot m^{-2}$
50	350	1.20	932	778	955	754	908	801
55	300	0.55	494	340	517	216	470	363
60	260	0.23	338	184	361	160	314	207
65	240	0.10	267	113	289	98	242	136
70	222	0.04	189	5	236	35	142	35
75	213	0.014	179	25	226	25	132	25
80	205	0.0044	167	13	214	13	120	13

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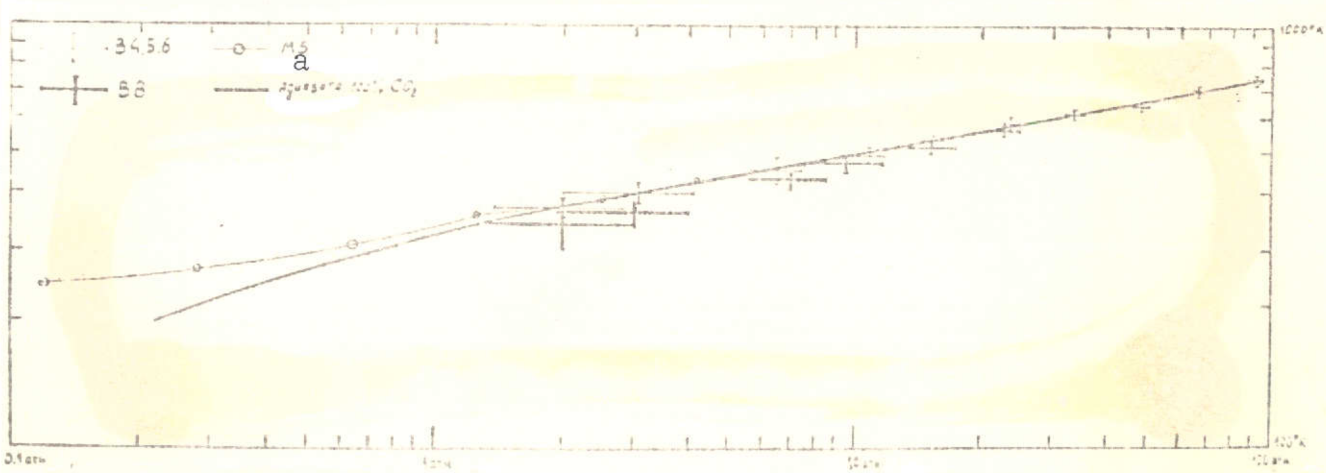

Fig. 1.

Key: a. Adiabat

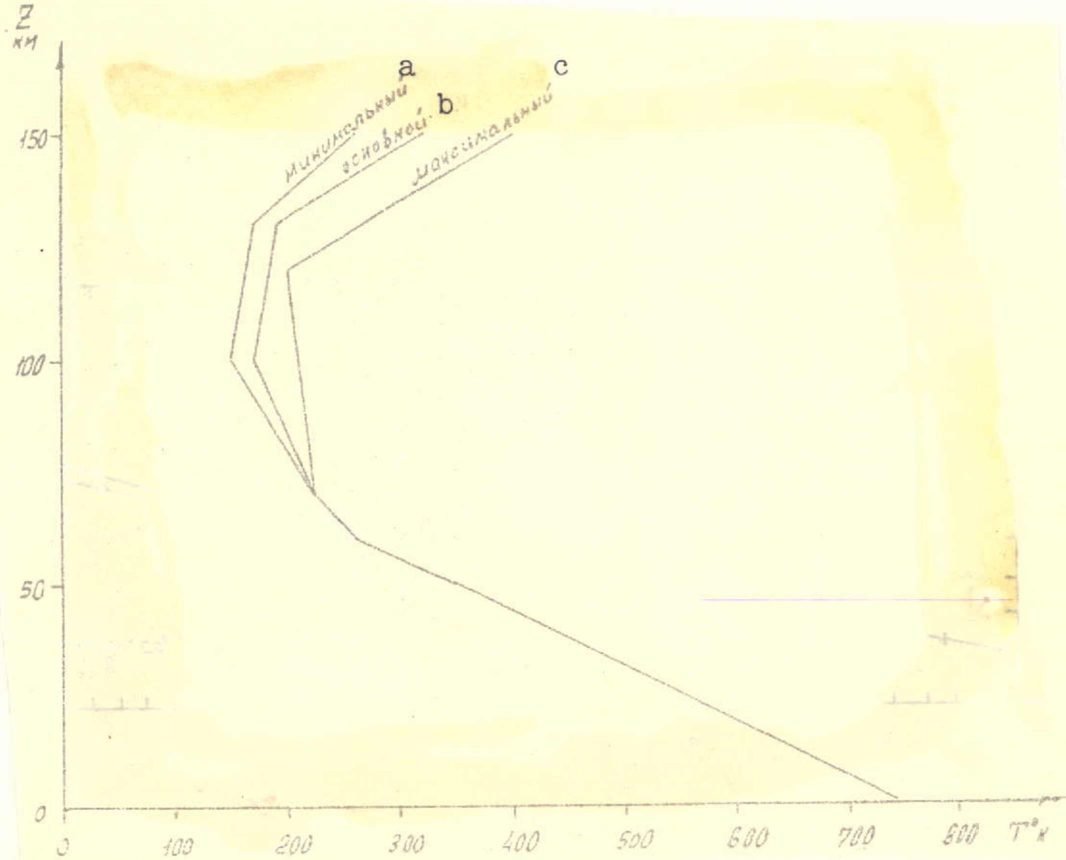

Fig. 2.

Key: a. Minimum; b. basic; c. maximum.

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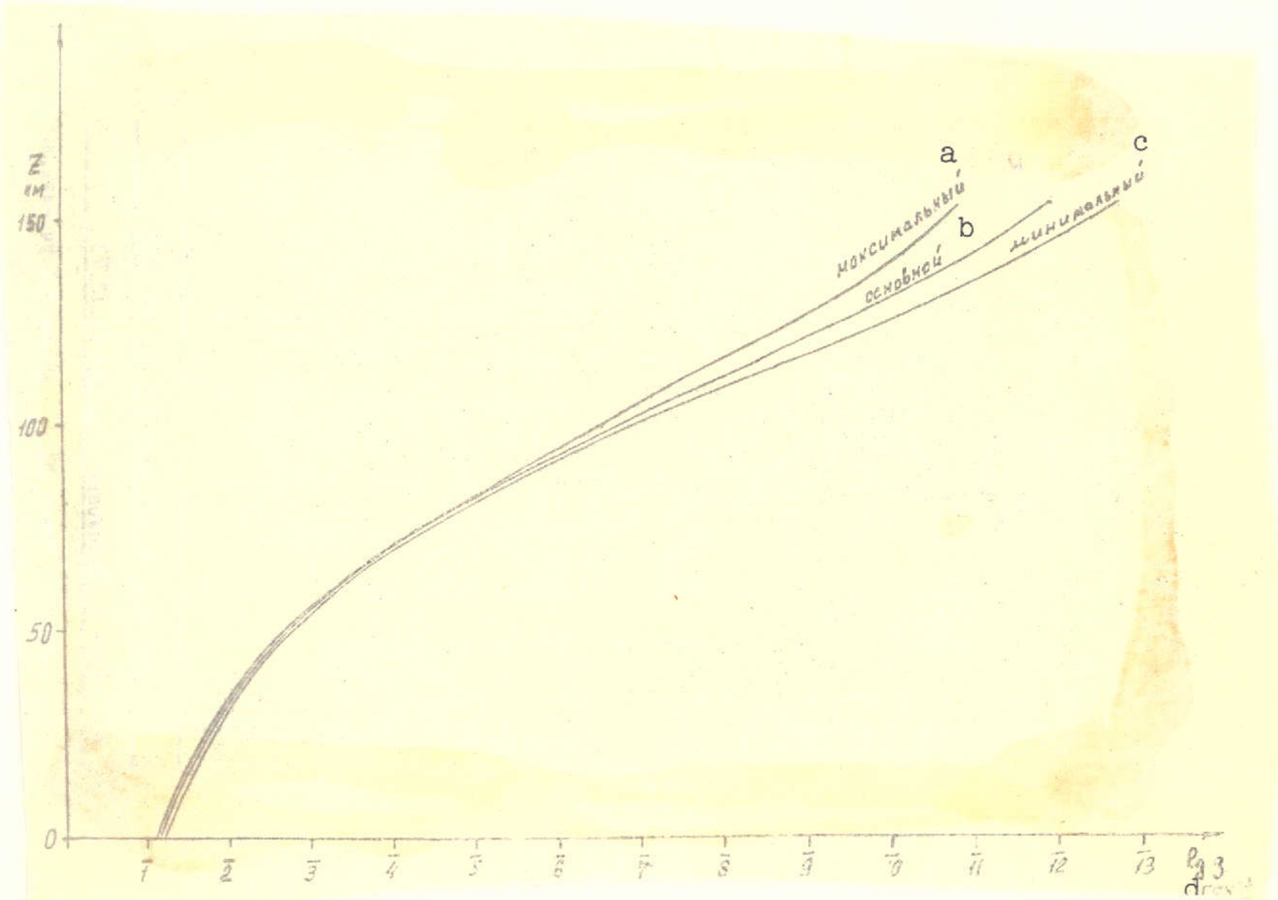

Fig. 3.

Key: a. Maximum; b. basic; c. minimum; d. g·cm^{-3}

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